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Assessing leaf nitrogen concentration of winter oilseed rape with canopy hyperspectral technique considering a non-uniform vertical nitrogen distribution

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ABSTRACT

Timely estimation of the vertical heterogeneity of leaf nitrogen concentration (LNC) from canopy reflectance using hyperspectral sensing is important for precision N management during winter oilseed rape productivity. However, current research pays little attention to LNC assessments by only taking LNC's vertical distribution into consideration, leading to limited accuracy and reduced applied value of the results. The main goal of this work was to quantitatively define the contributions of LNC in different layers to winter oilseed rape canopy raw (R) hyperspectra and to its transformation technique (i.e., first derivative reflectance, FDR), and develop a monitoring model considering the vertical LNC gradient using spectral data. Two field experiments were conducted for two consecutive years (2015–2017) with different N rates, cultivars and growth stages. At seedling and budding stage, canopy hyperspectral reflectance and LNC were measured *in situ*. Canopies of each treatment were divided into three layers of equal vertical (upper, middle, lower). Partial least square (PLS), lambda-lambda r^2 (LL r^2) and support vector machine (SVM) models were used to analyze the relationships between LNC in different layers and the hyperspectral reflectance measured from above the canopy. Field sampling revealed that a vertical distribution pattern of LNC existed, presenting an evident decline from the upper to lower layer. The FDR-PLS model for LNC prediction in different layers yielded a relatively higher accuracy compared to the R-PLS based on the full range hyperspectra, the coefficient of determination ($r^2{}_{val}$) was 0.872 for LNC in the upper layer, 0.903 in the middle layer, and 0.837 in the lower layer, with a relative percent deviation (RPD $_{val}$) of 2.794, 3.052, and 2.328, respectively. Finally, seven (437, 565, 667, 724, 993, 1084 and 1189 nm), six (423, 570, 598, 659, 725 and 877 nm), and five bands (420, 573, 597, 667 and 718 nm) were identified as effective wavelengths for assessing the vertical LNC distribution in the upper, middle and lower layer, respectively. The newly-developed SVM-FDR regression model using the effective wavelengths also performed well for upper ($r^2{}_{val}$ = 0.828, RPD $_{val}$ = 2.358), middle ($r^2{}_{val}$ = 0.844, RPD $_{val}$ = 2.556), and lower ($r^2{}_{val}$ = 0.781, RPD $_{val}$ = 2.029) layer LNC prediction. Our results indicate that estimation of LNC using hyperspectral reflectance data is most effective for the upper and middle layers of oilseed rape canopies. Moreover, the calibration model developed in this study has great potential to assess the N status of the whole oilseed rape canopy.

1. Introduction

Oilseed rape (*Brassica napus* L.) is a crucial industrial and oil crop usually grown for biodiesel and edible oil generation, with a production of about 14.4 million tones of seeds and a cultivated area of 7.5 million hectares in 2013 in China (Gu et al., 2016). Maintaining and developing the oilseed rape production are important for economic and food safety (Ren et al., 2017). Nitrogen (N) is the most limiting mineral nutrient for

Abbreviations: CHRS, canopy hyperspectral remote sensing; fAPAR, fraction of absorbed photosynthetically active radiation; FDR, first derivative reflectance; LL r^2, lambda-lambda r^2; LNC, leaf nitrogen concentration; ONLVs, optimal number of latent variables; PLS, partial least square; R, raw hyperspectra; RMSE, root mean square error; RMSECV, root mean square error of cross validation; RPD, relative percent deviation; r^2, coefficient of determination; VIP, variable importance in projection; SVM, support vector machine

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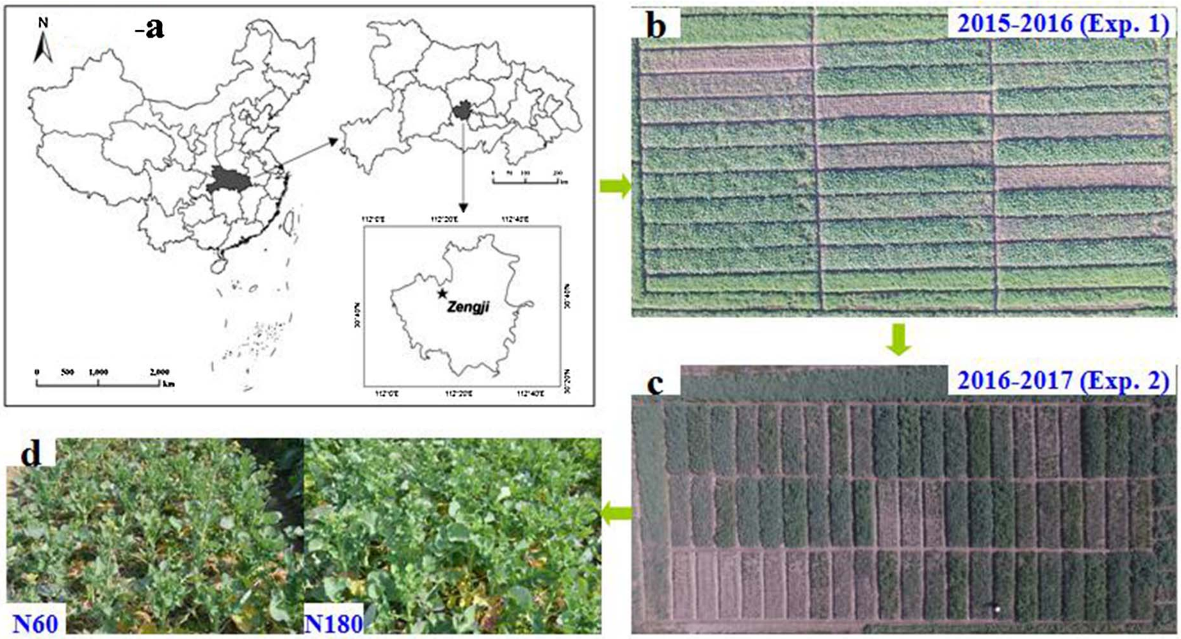

Fig. 1. Location of the experimental site (a), the aerial view of the field plots (b, c) and the close-up view of the field experiments (d).

oilseed rape growth and primary production. Moreover, the oil crop has a higher basic N demand (200–300 kg N ha^{-1}) than other farm crops because of its relatively high biomass and strong ability to uptake N (Yousaf et al., 2016). Leaf N concentration (LNC) is an important indicator for crop N status, agro-ecosystem productivity, crop photosynthesis and respiration (Martin et al., 2008). Therefore, dynamic assessment of crop LNC during the growing season is crucial for the regulation of fertilization in high-input and intensive agriculture, and provides an important opportunity for optimizing crop management strategies (Hansen and Schjoerring, 2003; Li et al., 2015). Traditional LNC measurements are based on chemical analysis techniques in the laboratory, which, despite being effective, are expensive, laborious, and time consuming, making them infeasible to obtain information on crop N status in time and at large scales (Song et al., 2016; Errecart et al., 2012). The canopy hyperspectral remote sensing (CHRS) technology enables non-intrusive and fast LNC estimation and has been widely applied for monitoring biochemical and biophysical growth indicators (Malenovský et al., 2009; Errecart et al., 2012; Oerke et al., 2016).

As one of the most mobile mineral nutrients, N exhibits a pronounced heterogeneity in its vertical distribution in crop canopies (Hikosaka et al., 1994; Winterhalter et al., 2012). If N demand of a crop is higher than its uptake, N is efficiently translocated to the photosynthetically most active leaves in the top canopy (Wang et al., 2005). Therefore, N deficiency generally occurs in the lower layer leaves, while excessive N will primarily influence the upper layer leaves (Huang et al., 2014). As light interception varies significantly between top and bottom of a crop canopy, LNC tends to be higher in upper layer leaves than in lower layer leaves even under sufficient N supply, in order to maximize light absorption and photosynthesis (Hirose and Werger, 1987; Chen et al., 1993). However, this vertical gradient is ignored by most top-of-the-canopy remote sensing techniques.

The prediction of LNC using CHRS technique is based on the relationships between canopy spectral characteristics and crop biochemical and structural features (Hoffer, 1978). The spectral reflectance of crops in the visible and near-infrared region (400–1300 nm) is primarily influenced by the upper layer leaves (Thomas and Gausman, 1977; Luo et al., 2016). Although the vertical heterogeneity of crop LNC has been recognized (Valentinuz and Tollenaar, 2004), the vertical N gradient in canopies has not been considered in hyperspectral sensing so far (Li et al., 2016a). This may affect the accuracy of LNC estimation by models derived from CHRS.

Different leaf layers make different contributions to the canopy hyperspectral reflectance, and, in turn, affect remote assessments of crop biochemical properties (e.g., LNC) (Jia et al., 2013; Zhao et al., 2017). It is crucial to define the contribution of specific leaf layers to the overall canopy reflectance spectra in order to increase the accuracy of the LNC estimation. However, the lack of comprehensive spectral information from lower canopy layers makes it difficult to obtain precise biochemical information from these layers, which may result in inconsistencies between the hyperspectral information and the corresponding nutritional features. Thus, many selected effective wavelengths are insensitive to the overall plant N status under moderate to high nutrition conditions (Thenkabail et al., 2000; He et al., 2016). To overcome this limitation, the relationship between the vertical distribution of LNC and canopy hyperspectral reflectance has to be considered in the development of prediction models derived from CHRS. This method could facilitate a timely and robust estimation of crop N status and help to improve fertilization management and resource use efficiency (Wang et al., 2005; He et al., 2016).

So far, little has been reported on the potential of CHRS-based models for in-season diagnosis of winter oilseed rape N status considering vertical gradients. This study aimed to evaluate the capabilities of CHRS to determine the vertical distribution of LNC within oilseed rape canopies. Particularly, we focused on the nature of LNC distribution in the crop canopy; whether or not the vertical LNC heterogeneity is influenced by the quantity of N fertilizer applied; and whether LNC of different layers could be quantified using CHRS technique. The specific objectives of this study were (1) to investigate the relationship between LNC in different layers and the top-of the-canopy hyperspectral reflectance information, (2) to analyze the contribution of LNC in different layers to canopy reflectance, (3) to identify the most important wavelengths for prediction of LNC in different layers, and (4) to establish a CHRS model using the identified effective wavelengths for evaluating LNC of the whole oilseed rape canopy based on the vertical distribution patterns of LNC.